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Fifteenth Annual Report

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Department of Electrical Engineering
Columbus, Ohio 43212

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I. DIRECTORS OVERVIEW

This report represents the fifteenth annual summary of The Ohio State University Joint Services Electronics Program (JSEP).

There have been a total of 31 Ph.D. and 23 M.Sc. degrees in Electrical Engineering obtained under partial JSEP sponsorship. There are currently 6 Ph.D. and 2 M.Sc. students being partially supported under JSEP.

As may be seen in the Annual Report Appendix, 15 reprints have been included for the period September 1991 to September 1992. In addition, 7 papers have already been accepted for publication in the coming year, an additional 11 papers have been submitted, and an additional 11 papers are in preparation.

II. DESCRIPTION OF SPECIAL ACCOMPLISHMENTS AND TECHNOLOGY TRANSITION

The transfer of the compact range and target identification technology initiated under JSEP support for time domain studies continues to make large advances. The installation of a large compact reflector and a modern radar of our design is near completion for ASD at Wright Patterson Air Force Base. This system will have all of the sensitivity of the Mini Range reported last year and yet has a 14′ quiet (or target) zone. The reflector includes all the most updated features of the ESL design. It is the range we would like to have, but can never afford.

We are also assisting Rockwell (Tulsa) to update their RCS facilities. This work is on a subcontract to the ESL from the Air Force. These and other advances were only possible because of the initial JSEP support. This continues to be a case where a small investment of basic research funds have been leveraged to generate much larger support and have achieved major contributions for DoD. This has also lead to OSU-ESL involvement in the study of Ultra Wide Band radar systems.

Our target identification work, also partially funded at one time under JSEP Time Domain Studies, is also being funded by several other agencies including ONR and continues to be rather vigorous. Prof. Peters participated in an ARO workshop on Mine Detection and one of the conclusions was that these target identification schemes be pursued for mine detection purposes. Again, JSEP funds have been leveraged to initiate larger programs which have been supported continuously since JSEP funding was terminated.

The Adaptive Array Work Unit has been cancelled on the retirement of Professor Compton. At the suggestion of Dr. Ken Davis, the funds for this work unit have been divided among the other work units. This move partially corrects the inflationary erosion of funding for these work units. Prof. Ri-Chee Chou has resigned to assume a post in industry. However, his work unit will not be affected since he was working with Prof. Pathak.

The research activities devoted to the Generalized Ray and Gaussian Beams continues to be expanded by external funding. This program is being expanded by use of such funds which are more focussed on the requirements of the sponsors which include both the Air Force and the Navy.

It becomes clear from the above that a major portion of technology transition of JSEP research takes the form of additional supported research from other DoD agencies. Other forms of transition include former graduate students, who upon graduation are employed in DoD related positions, and publications of results of JSEP research. Yet another form of such transition is represented by computer codes that incorporate the results of our research. These complex codes are available to DoD related industries for a nominal fee of $250. Last year 97 such codes were issued.

Our JSEP research continues to focus on electromagnetic related topics. There are four major electromagnetics areas that were pursued in the past year.

The Diffraction Studies Work Unit has initiated research on a time domain version of the Uniform Theory of Diffraction. This time domain version (TD-UTD) has a major potential flaw when the rays pass through a caustic, in that the fields become non-causal. However, the fields in the causal region are correctly predicted. This has led to the development of a means of discarding the non-causal component and this is currently under investigation. This TD-UTD solution should be most useful in predicting the early time signals and providing physical insight to various scattering processes.

A second topic under the Diffraction Studies Work Unit involves further extensions of the Generalized Resistive Boundary Condition (GRBC) and the Generalized Impedance

Boundary Condition (GIBC). These have been applied to scattering from a chiral slab. The generalized junction condition has been used to obtain a solution for perfectly conducting strip with a thin dielectric coating on either side. This has previously been treated only by the very complex Maliuzhinets' solution. This can now be used to treat more complex geometries.

A third topic of interest is the diffraction from a corner. Several solutions have been recently developed. The current refinement makes the scattering from a more complex corner, such as found in a pyramid, treatable.

A fourth task involves the reflection/diffraction of a Gaussian beam. This represents an approach to replace the usual ray optics solution for very complex geometries where the versatile ray optics solution becomes cumbersome.

The Integral Equations Work Unit has been focussed on evaluating the electrical properties of a 3-D artificial dielectric where the artificial media has been constructed from a variety of periodic shapes (rods, loops, crosses, tees, etc.). Currently, the analysis has been applied to a 3-D periodic array of small spheres. Both the permittivity and the loss tangent have been evaluated. This effort has proven useful to a welding engineering group who have an interest in welding modern materials, i.e., polymers. A lossy gasket is made by doping a lossless polymer. The solution makes it possible to compute the heat generated in the gasket so that a bonding action can be achieved. Research is now being directed to include arbitrarily-shaped small periodic scatterers.

Finite Element Techniques represent an area where the electromagnetics community has focussed much attention in the past few years. They are particularly suited for analyzing the scattering from penetrable bodies of arbitrary shape with arbitrary inhomogeneities. However, the ultimate goal of treating 3-D targets that are very large in terms of wavelength has not been achieved. This work unit is currently focussed on two approaches for extending the capability of the Finite Element Techniques. The first approach consists of using a reduced matrix size and attempting to correct the resulting errors. In the second approach, the target is segmented, each segment is treated separately and finally, the solutions from all the segments are coupled to form another matrix which can be solved efficiently.

The Hybrid Studies Work Unit involves a cooperative effort for most of the researchers involved in other work units. The goal is to combine techniques for radiation/scattering from geometries for which no single solution would be practical. In the past UTD-MM and MM-UTD solutions have been developed and are currently being employed to analyze stripline antennas. Of current interest are curved (or conformal) substrates as well as an MM-UTD approach for analyzing scattering from large bodies with appendages, i.e., fins or stabilizers. Other appendages and antenna windows are also of interest. Hybrid techniques that combine analytical methods with the generalized scattering matrix are also under development as are hybrid combinations of high frequency ray techniques with the Finite Difference Time Domain (FDTD) solutions. The combinations of these various methods each offer unique possibilities to further understanding and evaluation of scattering/radiation mechanisms.

III. DIFFRACTION STUDIES

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1. Introduction

Until recently, the research effort in significantly expanding the uniform geometrical theory of diffraction (UTD) area (which primarily evolved at The Ohio State University [1, 2]), largely under JSEP support, was mostly confined to developing UTD based ray solutions in the frequency domain. During the present period, work has been initiated to develop a UTD directly for the time domain. Such a time domain UTD is highly desirable because it would directly provide a solution for the early to intermediate time transient response of relatively complex, pulse excited, antenna and scattering configurations which are large compared to the smallest wavelength of the frequency spectrum contained in the electromagnetic pulse, and it would also provide the same physical insight that a frequency domain UTD ray solution does. The frequency domain UTD which is valid for intermediate to high frequencies indicates that a time domain UTD would be valid for precisely these early to intermediate times. In contrast, the more conventional approach of employing the numerical fast Fourier transform (FFT) inversion of frequency domain solutions to obtain the corresponding time response, as well as the use of direct numerical time domain methods are expected to be far less efficient and less physically transparent. Direct time domain solutions are of great interest in the area of short pulse technology for radar target identification, remote sensing and other applications. An important question regarding the non-causality of the time response which results upon inverting the frequency domain ray fields that pass through ray caustics has been recently addressed and progress has been made to arrive at a better understanding of this problem and some possible remedies. This important question needs to be resolved before one can truly develop a general time domain UTD for curved edges and many more basic or canonical geometries which can exhibit caustics, in physical space, of rays reflected and diffracted from such structures.

The time domain UTD discussed above will in most cases be developed by "analytically" (as opposed to numerically) transforming the corresponding frequency domain UTD solutions, except in those special situations where a closed form analytical UTD solution can be constructed directly in the time domain. Consequently, it is just as important to continue the development of the frequency domain UTD to eventually obtain a wide class of useful time domain UTD solutions. While a lot has been achieved in the development of frequency domain UTD solutions, more remains to be done. The latter is essential since high frequency methods still command attention as an area in their own right because of the impact they have already had and will continue to have in practical DoD related applications, and eventually also to some important remote sensing applications. At present, work is continuing on an important extension to the UTD solution obtained about two years ago, under JSEP support, for analyzing the rather complex canonical corner diffraction phenomenon when the corner resides in a perfectly conducting planar geometry. The extension presently under study would allow the corner to reside in a pyramidal structure or in some other more general structure which can be built up from planar facets, thereby providing another significant step in extending the range of applicability of the UTD to accurately analyze complex electromagnetic high frequency radiation and scattering phenomena for which exact analytical solutions cannot be found.

The development of UTD solutions for the diffraction by edges or discontinuities in planar material media which are penetrable has continued, and new solutions have been obtained for the more difficult case of a plane wave obliquely incident on a class of thin planar materials with junctions (or edges). The solutions to these types of scattering configurations constitute the first step in extending the UTD to deal with diffraction by more complex media with discontinuities, rather than by just perfectly-conducting structures. This is a very timely topic since many parts of modern aerospace vehicles are being constructed from materials which can be categorized as being complex penetrable media.

2. Time-Domain UTD

The development of analytical solutions for predicting the transient radiation or scattering of electromagnetic pulses from complex objects is desirable because not only will they be more efficient but they would also provide more physical insight than corresponding numerical solutions. However, exact analytical solutions can be obtained only for a very limited number of transient radiation/scattering configurations. On the other hand, it appears feasible, in general, to analytically invert into time domain the corresponding asymptotic high frequency ray solutions such as those based on the UTD; this has been shown for some special cases by Kouyoumjian and Verrutipong [3]. Such analytical inversion of frequency domain based UTD solutions into the time domain (TD) are valid for early to intermediate times after the arrival of the wavefronts corresponding to the different frequency domain ray mechanisms. Such early time analytical solutions can, in principle, be combined into a hybrid scheme whereby the late time response may be found via numerical solutions of the governing space time integral or differential equations. While the development of an early to intermediate time response for radiation and scattering by analytically inverting the frequency domain based UTD solutions into the TD is clearly useful so that a highly efficient and physically transparent progressing wave or TD-UTD can be developed for complex objects, there remains an underlying difficulty in such a procedure which needs to be resolved before it can be implemented to deal with general situations. This difficulty arises from the fact that a frequency domain based UTD ray field undergoes a constant phase jump of $\pm\frac{n\pi}{2}$ for all (positive/negative) frequencies whenever it passes through an odd number ($= n$) of ray caustics along its propagation path, thereby violating the Hilbert transform relation, and provides upon inversion to the TD a transient field which is non causal! A preliminary study has been performed to address this important question of non-causality. In particular, a few configurations have been analyzed such that they provide good reference solutions in closed form which are causal, even though the corresponding TD-UTD solutions obtained for these cases by analytically inverting the frequency domain UTD solutions containing caustic effects become non-causal. One of the examples which has been treated is a two-dimensional concave parabolic reflector illuminated on axis by an impulsive plane wave. The exact analytical TD solution based on a valid physical optics approximation for this case reveals upon comparison with the corresponding analytical TD-UTD solution that the TD-UTD is non-causal for axial observation points beyond the focus (caustic) as expected; however, the causal part of the TD-UTD solution which compares well with the reference solution is not really affected by the presence of the non-causal part. Furthermore, it is seen from the reference solution that there is a precursor that exists prior to the arrival of the UTD wavefront for the reflected component, but that this precursor is causal. Also, the reference solution provides a physical basis for turning off the non-causal portion of the TD-UTD solution so that a rule can be established as to when the non-causal TD-UTD should really be turned on, to properly contain only the "causal precursor". An extension to this example which is currently under investigation is a curved surface containing an edge and a discontinuity in surface derivative (i.e., a higher order edge), respectively, to establish additional confidence in the rule for turning on the non-causal TD-UTD so that it can contain only a "causal precursor" to the arrival of the wavefront (which passes through a caustic). This curved surface containing an edge (and also higher order edge) type discontinuity within its boundaries exhibits a far more general situation (as may occur on a more complex object) than is possible with just a simple concave parabola of finite width. One other reference example which has been analyzed recently is the hypothetical radiation from an impressed circular ring current source which exhibits a caustic in the frequency domain. This example, which serves as a reference, can be treated exactly in an analytic fashion in the frequency domain, and it also provides an exact analytical solution in the time domain. Again, the corresponding TD-UTD solution obtained via analytical inversion of the high frequency UTD solution for this case exhibits, for an off-axis observer, a non-causal response, but the reference solution again provides the same physical guidelines as in the other example of the parabola for making the TD-UTD causal so that it contains only a "causal precursor" to the arrival of the wavefront (which passes through the axial caustic of the ring source).

It is necessary to work out such reference TD solutions which have closed analytical expressions so they can in each case be compared with the corresponding closed form TD-UTD solutions to eventually establish proper guidelines for making the TD-UTD causal for more general and more complex situations. It is noted that the non-causal TD-UTD behavior for caustic situations is due to the lack of sufficient low frequency information in the UTD frequency domain solutions which are analytically inverted into the TD. Obviously, the frequency domain UTD, which is a high frequency technique, will therefore inherently lack this low frequency information. Other approaches to augment the high frequency UTD caustic solution with low frequency information which must be obtained from entirely separate considerations has not yet been investigated and does not appear at this time to be as useful and as general an approach as is currently being investigated; however, this other approach will also be investigated in the future phases. Subsequently, a TD-UTD will be developed for the general situation of curved edges in curved surfaces (since this geometry is one of the most frequently encountered) and a causal solution will be obtained even for ray fields passing through caustics of reflected and diffracted rays.

3. UTD for Diffraction by Edges in Planar Dielectric/Magnetic Materials

The study of the high frequency scattering by non-conducting and penetrable surfaces with edges or discontinuities in its electrical properties has continued. The main steps of the scheme are the following. First, to somewhat simplify the analysis, the scatterer with edges or electrical discontinuities is replaced by a generalized impedance/resistive boundary condition. The resulting mixed boundary value problem is then solved by any of several functional analytic techniques, i.e., Wiener-Hopf method, Maliuzhinets' method, etc. The last step is of course to develop the diffraction coefficients by asymptotically evaluating the integral expressions resulting from the solutions of the corresponding mixed boundary value problems. In the last year, the following results have been obtained:

(a) Generalized impedance boundary conditions (GIBC) for a perfect electric conducting (PEC) backed planar chiro-dielectric slab have been developed. These boundary conditions can be used to solve scattering problems (where the fields outside the scatterer are of interest) without solving for the fields inside the body. Generalized resistive boundary conditions (GRBC) have also been developed for a planar chiro-dielectric slab which can transmit electromagnetic energy. These GRBC are also useful to solve problems of electromagnetic (EM) scattering by a chiral slab.

(b) When GIBC/GRBC are used to study the EM diffraction by thin slabs with edges, the solutions contain some unknown constants even after the radiation, boundary and usual edge conditions have been imposed. Last year, a generalized junction condition has been developed to solve for these unknown constants. This generalized junction condition has been used to completely solve the diffraction by a PEC strip coated on both sides with different thin material slabs. This problem cannot be solved by the Wiener-Hopf technique without having to solve a matrix Wiener-Hopf equation which is extremely complicated. For this problem, the more suitable method is the reflection or Maliuzhinets' method. The Maliuzhinets' method was combined with the generalized edge condition to obtain a solution for the diffraction by a PEC half-plane coated on both sides with thin, but different material slabs. Since the strip has two edges, the interaction between these two points of diffraction needs to be taken into account. Thus, a modified spectral ray method was used to obtain the doubly and triply diffracted fields. To assess the accuracy of these results, the fields scattered by this strip were calculated with the Maliuzhinets' based solutions as well as with a moment method based solution. The agreement between these two solutions is very good.

The development of this generalized junction/edge condition is very important because it eliminates the need to impose the reciprocity condition in the analysis (as was done in the past) and allows for the evaluation of all the unknown constants in the spectral integral. Note that in most papers found in the literature, some of these unknown constants are arbitrarily set equal to zero.

4. Extensions of UTD

It was indicated previously in the introduction that it was necessary to continue to extend the applicability of the UTD method, not only because it has emerged as a powerful tool for analyzing the radiation/scattering from rather complex, realistic radiating objects, but also because of its use in constructing the new time domain UTD (or TD-UTD), as well as for combining UTD with other low frequency methods through systematic hybrid procedures.

One of the most challenging configurations being analyzed at the present is the diffraction by a corner in a perfectly-conducting surface. About two years ago, a UTD based coefficient was obtained to describe the diffraction of waves by a corner in a perfectly conducting planar surface. That solution is undergoing additional refinement (largely through collaboration with Prof. Tiberio at the Univ. of Florence, Italy). This refinement maintains the same new UTD corner transition function obtained earlier; however, the refinement allows the UTD solution to be extended to treat a corner not just in a single planar surface but also in a pyramid, or a corner in a more general structure formed by different planar surfaces. This work, which is currently under progress, would constitute a significant extension of the previous result obtained for predicting boundary corner diffraction phenomena when the corner resides in a planar boundary.

Another study which is in progress is the reflection and diffraction of Gaussian beams by curved perfectly conducting surfaces containing smooth edges. This study is important because there are many special situations where the UTD ray method, versatile as it is, will become cumbersome. (Examples of the latter situation occur, for instance, in the analysis of large reflector antennas with array feeds, and for interior cavity coupling and propagation analysis, etc.) Consequently, simple beam optics type solutions have been obtained for the reflection of electromagnetic Gaussian beams from two- and three-dimensional curved surfaces. In the case of two-dimensional surfaces, the expressions for the diffraction of the incident Gaussian beam by the edges have also been developed and shown to work properly. It is noted that the diffracted field contains composite effects of reflection by the surface near the edge and of the diffraction by the edge itself; neither of these effects can be described directly in terms of a Gaussian beam; i.e., the Gaussian beam "breaks up" upon diffraction. The shadow boundary effects associated with the edge when it is excited by a Gaussian beam are more complicated than for ray field excitation; nevertheless, the present, closed form beam optics result provides a proper behavior for the fields in the shadow boundary. In the case of the three-dimensional situation, the incident Gaussian beam is allowed to be arbitrarily polarized and to have an astigmatic character. At the present time, an analysis of the diffraction of the general three-dimensional electromagnetic, astigmatic Gaussian beam is in progress. It is hoped that these beam reflection and diffraction solutions will provide tools to solve a class of problems which may not be best suited via the conventional UTD method; examples will be treated to illustrate these cases.

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5. Diffraction Studies — JSEP Publications

Published refereed journal papers:

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2. P.H. Pathak, "High Frequency Techniques for Antenna Analysis," *Proceedings of IEEE*, vol. 80, no. 1, January 1992, pp. 44–65, (invited paper).

3. R.G. Rojas, "Integral Equations for the Scattering by a Three Dimensional Inhomogeneous Chiral Body," *Journal Electromagnetic Waves and Applications*, vol. 6, no. 5/6, July 1992, pp. 733–750.

Accepted refereed journal papers:

1. R.G. Rojas and M. Otero, "Scattering by a Resistive Strip Attached to an Impedance Wedge," *Journal of Electromagnetic Waves and Applications.*

2. H.C. Ly and R.G. Rojas, "Analysis of Diffraction by Material Discontinuities in Thin Material Coated Planar Surfaces based on Maliuzhinets' Method," *Radio Science.*

3. H.C. Ly, R.G. Rojas and P.H. Pathak, "EM Plane Wave Diffraction by a Planar Junction of Two Thin Material Half-Planes — Oblique Incidence," *IEEE Trans. on Antennas and Propagation.*

Oral presentations:

1. L. Peters, Jr., "Historical Review of ElectroScience Laboratory with an Emphasis on Contributions of R.G. Kouyoumjian," 1992 IEEE APS/URSI International Symposium, Chicago, Illinois, July 1992 (invited).

2. R.G. Kouyoumjian, "A Brief History of the UTD — Focus on Edge Diffraction," 1992 IEEE APS/URSI International Symposium, Chicago, Illinois, July 1992 (invited).

3. P.H. Pathak and R.J. Burkholder, "On the Question of Time Causality for HF Ray Fields Traversing Caustics," 1992 IEEE APS/URSI International Symposium, Chicago, Illinois, July 1992 (invited).

4. P.H. Pathak and R.J. Marhefka, "On the Behaviour of Uniform Ray Solutions at Lower Frequencies," 1992 IEEE APS/URSI International Symposium, Chicago, Illinois, July 1992 (invited).

5. H.C. Ly, R.G. Rojas and P.H. Pathak, "Diffraction from a Two-Part Planar Material Junction: Oblique Incidence Case," 1992 IEEE APS/URSI International Symposium, Chicago, Illinois, July 1992.

6. R.G. Rojas and M.F. Otero, "EM Scattering by a Chiro-Dielectric Body of Arbitrary Shape in the Presence of an Impedance Wedge," 1992 IEEE APS/URSI International Symposium, Chicago, Illinois, July 1992.

7. H.C. Ly and R.G. Rojas, "Application of the Maliuzhnets' Method to Diffraction Problems involving Generalized Impedance Boundary Conditions," 1992 IEEE APS/URSI International Symposium, Chicago, Illinois, July 1992.

8. P.H. Pathak and Y. Rahmat-Samii, Short Course on Asymptotic High Frequency, 1992 IEEE APS/URSI International Symposium, Chicago, Illinois, July 1992 (invited).

IV. INTEGRAL EQUATION ANALYSIS OF ARTIFICIAL MEDIA

Researchers:

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1. Introduction

This section will summarize our work in integral equation studies from September 1991 to September 1992. In overview, our recent research has centered on integral equation and method of moments (MM) solutions for artificial media. In particular, we have developed a flexible and accurate integral equation and method of moments procedure for determining the effective permittivity and permeability of artificial media. The method has been applied to artificial media composed of 2-D dielectric rods, short perfectly conducting dipoles [1], and small lossy dielectric spheres [2]. At present we are developing method of moments techniques for determining the effective permittivity and permeability of artificial media constructed from thin material rods of arbitrary configuration (i.e., straight rods, loops, crosses, tee's etc.).

As illustrated in Figure 1, an artificial medium is created by suspending a large number of small scatterers, such as spheres, discs, or dipoles, in some host or background medium. For computation convenience, the small scatterers are assumed to be on a periodic lattice. An electromagnetic field in this artificial medium will induce currents to flow on or in the small scatterers. In this case, each of the scatterers can be viewed as having a small electric and/or magnetic current moment, and thus the array can be viewed as having some net electric dipole polarization **P** per unit volume and/or magnetic dipole polarization **M** per unit volume. Essentially, the macroscopic scatterers in the artificial medium are equivalent to the atoms and molecules in a real medium. Assuming for simplicity that the artificial medium is isotropic, in the artificial medium, the electromagnetic field vectors are related

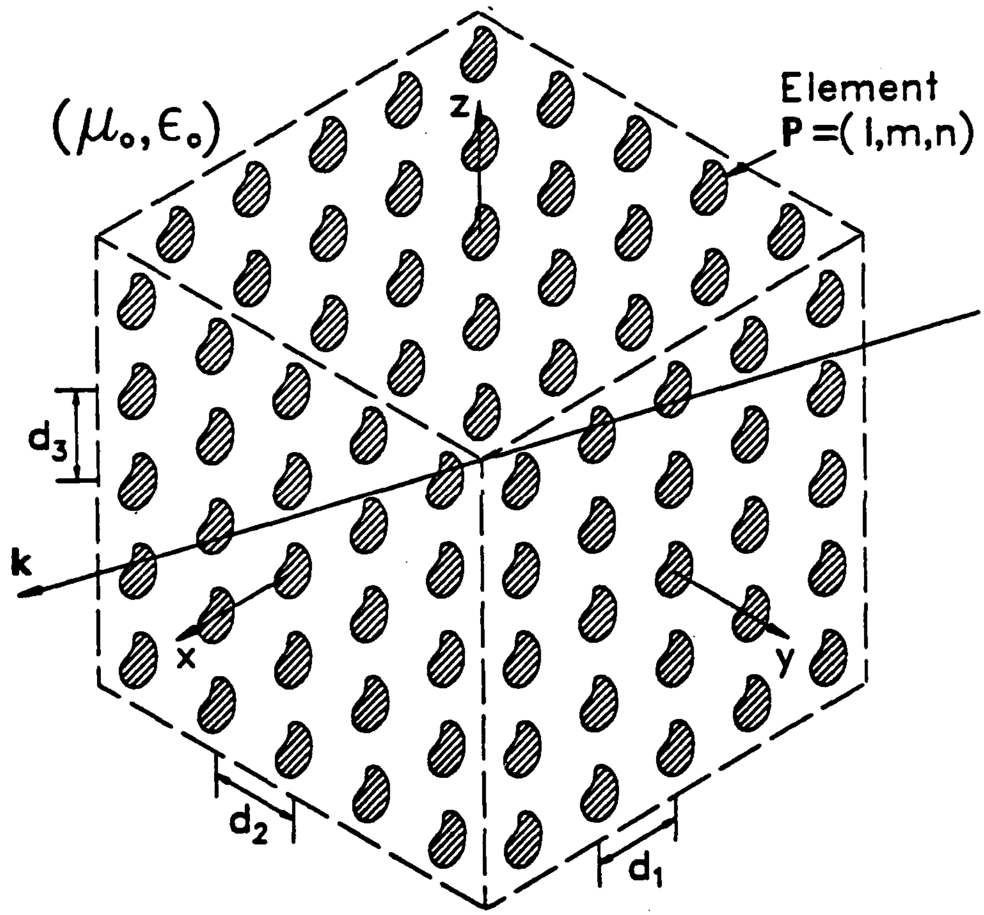

Figure 1: An artificial medium is modeled by a periodic array of small scatterers.

by

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P} = \epsilon_{eq} \mathbf{E} \tag{1}$$

$$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) = \mu_{eq} \mathbf{H} \tag{2}$$

where (μ_0, ϵ_0) are the constitutive parameters of the background or host medium and $(\mu_{eq}, \epsilon_{eq})$ are the equivalent permeability and permittivity of the artificial medium.

The main purpose of our research is to determine $(\mu_{eq}, \epsilon_{eq})$ as a function of:

1. the size, shape, and material composition of the small scatterers,

2. the density of the small scatterers,

3. the frequency, and

4. the field polarization.

When this is complete, we will be able to consider the problem of designing or "engineering" an artificial medium to have some prescribed $(\mu_{eq}, \epsilon_{eq})$. Another potentially interesting problem is the inverse problem. That is given $(\mu_{eq}, \epsilon_{eq})$ of an artificial medium (say by measurements) what can be deduced concerning the properties of the small scatterers.

2. Current Research

At present we are considering an artificial medium composed of thin dielectric rods of essentially arbitrary shape in a periodic lattice. It is assumed that a plane wave is propagating in the artificial medium in a given direction. However, since the equivalent permittivity and permeability of the artificial medium are unknown, the propagation constant γ_{eq} of this wave is unknown. The objective of the solution is to find this propagation constant, from which $(\mu_{eq}, \epsilon_{eq})$ can be deduced.

Our method of solution is based upon an essentially exact full wave analysis. The first step is to use the volume equivalent theorem to replace the array of small scatterers by the background medium and unknown equivalent electric polarization currents. These unknown polarization currents can be formulated as the solution to a volume integral equation. This integral equation is exact and includes all interactions between the elements in the triple infinite periodic array. However, due to the periodicity of the problem, the only unknown is the current in the center element, and the volume integral equation need only be enforced in the center element.

The integral equation is solved by a numerical technique known as the method of moments (MM). Essentially, the unknown current is expanded in terms of N basis or expansion functions, and the integral equation is enforced for N weighting or testing functions. The result is that the integral equation is reduced to an order N matrix equation

$$[Z(\gamma_{eq})]I = V \tag{3}$$

where $[Z]$ is the order N impedance matrix, V is the length N excitation vector, and I is the length N current vector which holds the coefficients in the original expansion for the current. As is emphasized in Equation 3, the impedance matrix is a function of the unknown propagation constant γ_{eq}.

Since a plane wave is a solution of Maxwell's *source free* equations, we seek a solution of Equation 3 for which the excitation vector $V = 0$, i.e.,

$$[Z(\gamma_{eq})]I = 0. \tag{4}$$

Such solutions can be termed the normal or natural modes of the artificial medium, and are only possible if the determinant of the impedance matrix is zero, i.e.,

$$\det|Z(\gamma_{eq})| = 0. \tag{5}$$

Equation 5 must now be solved in an iterative fashion for γ_{eq}. Once γ_{eq} is known, $(\mu_{eq}, \epsilon_{eq})$ can be found. For the simple case in which the artificial medium is non-magnetic ($\mu_{eq} = \mu_0$), then

$$\gamma_{eq} = j\omega\sqrt{\mu_0\epsilon_{eq}} \rightarrow \epsilon_{eq} = -\frac{\gamma_{eq}^2}{\omega^2\mu_0}. \tag{6}$$

3. Example Result

Recently we applied our methods to determine the effective permittivity of an artificial medium composed of small lossy dielectric spheres. This work was done in association with the welding engineering group at Ohio State University. This group is using doped conducting polymers to RF weld polymer bars. A lossy gasket is made by doping an otherwise lossless polymer with small lossy conducting particles. The problem is to determine the effective loss tangent of the gasket, so that one can compute the heat generated in the gasket to perform the weld. We modelled the doped gasket as an artificial dielectric composed of small lossy spheres. Figure 2 shows a typical result in which we consider an artificial medium composed of small spheres of diameter $0.001\lambda_0$ on a triple periodic lattice of spacing $0.01\lambda_0$. The figure shows the effective relative permittivity and loss tangent of the artificial medium as a function of the loss tangent of the spheres. Note that as the loss tangent of the spheres increases, the loss tangent of the artificial medium initially increases, reaches a maximum, and then falls to zero. Thus, there is a specific sphere loss tangent which results in maximum loss tangent of the artificial medium.

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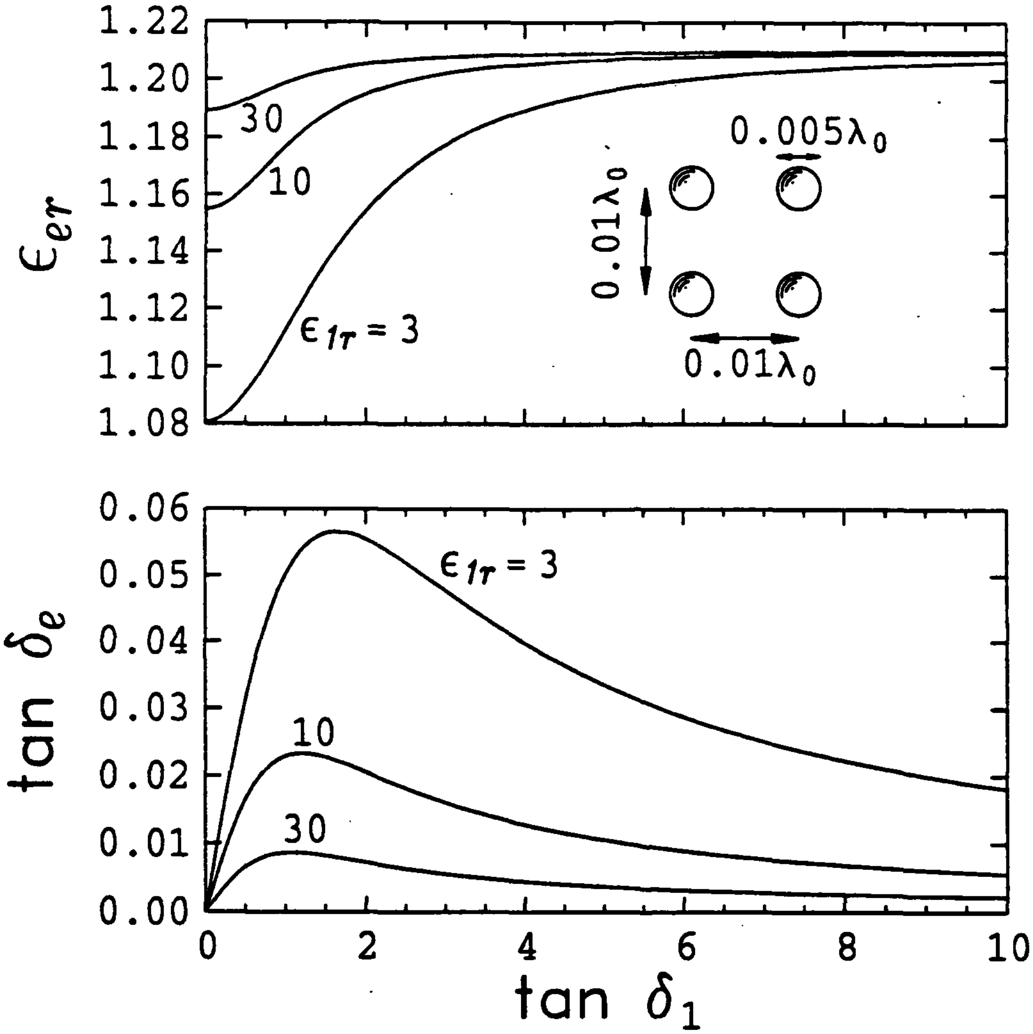

Figure 2: Effective permittivity versus sphere loss tangent.

V. FINITE ELEMENT TECHNIQUES

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1. Introduction

In Work Unit III, we are developing finite element techniques for the solution of electromagnetic scattering from electrically large penetrable objects. The finite element method (FEM) is easily coupled to sophisticated mesh generators that allow a user to consider geometries of arbitrary shape as well as geometries with arbitrary inhomogeneities. In addition, FEM is well suited for solving geometries involving a large number of unknowns because the resulting matrix equation is both sparse and banded. However, in many cases the matrix size is so large that a direct matrix solution is computationally infeasible even though the matrix is sparse.

We propose two techniques to reduce both the computation time and memory requirements for FEM. In the first method, the error is predicted with a posteriori information to improve the accuracy of the solution. Thus, a smaller number of unknowns can be used to produce an inaccurate solution which can then be corrected to the desired accuracy by the proposed scheme. The degree to which the method predicts the error is studied and presented below.

The second method is a partitioning scheme in which the geometry is divided into many sections. A set of FEM problems is solved within each section independent of the other sections. The solutions from all the sections are then coupled to form a matrix equation which is block tridiagonal. The block tridiagonal matrix can be solved very efficiently with algorithms which take advantage of the matrix structure. The initial results indicate that this method can significantly reduce the computation time compared to a direct solution of the entire geometry where LU decomposition is used to solve the FEM matrix equation. The details of this partitioning scheme are presented below.

The final topic of this report is the development of a boundary truncation method for three-dimensional electromagnetic scattering from complex penetrable objects. Since FEM is formulated as a boundary value problem, the boundary conaitions on the mesh must be known. For the scattering problem, the boundary conditions are specified at infinity (Sommerfeld radiation condition). Unfortunately, we cannot choose a finite element mesh that extends to infinity. Instead, the mesh is truncated close to the scatterer, and additional constraints are imposed on the boundary to properly account for the radiation condition. One boundary truncation method that has proven to be efficient in two dimensions is the bymoment method [1]. We are currently in the process of extending the bymoment method to three-dimensional problems.

The eventual goal is to couple the three techniques that have been described, so that the problem of electromagnetic scattering from electrically large three-dimensional objects is feasible. In addition to the major topics presented in this report, several secondary projects that indirectly aid the electrically large problem are currently being considered as well as initiated. One is the work being performed on discretization error. Discretization error analysis provides a tool for determining the relationship between the mesh density and the accuracy of the solution. At this time, we have analyzed the effect of boundary conditions on discretization error. Work is being performed on the development of a dispersion analysis model for edge elements because these elements can be used advantageously for many geometries. In addition, we are beginning research into the use of parallel computers for the partitioning scheme presented above and for time domain simulations of high-speed circuits.

2. A Posteriori Error Prediction for FEM

From Maxwell's equations, it can be shown that the electric field satisfies the differential equation

$$\nabla \times \left(\frac{1}{j\omega\mu}\nabla \times \vec{E}\right) + j\omega\epsilon^* \vec{E} - \nabla\left(\frac{1}{j\omega\mu\epsilon^*}\nabla \cdot (\epsilon^* \vec{E})\right) = 0 \tag{7}$$

where $\epsilon^* = \epsilon - j\sigma/\omega$. Although the third term in 7 is zero, it must be used in the finite element method to eliminate non-physical spurious solutions [2].

A finite element solution can be computed from 7 where the electric field is approximated with standard finite element shape (basis) functions. Unfortunately, because the shape functions are only finite order polynomials with C^0 continuity (Function is continuous, but first derivative is discontinuous.), it produces a numerical solution which only approximates the real solution. Let the finite element approximation for the electric field be denoted by $\tilde{E}$. Then $\tilde{E}$ satisfies the equation,

$$\nabla \times \left(\frac{1}{j\omega\mu}\nabla \times \tilde{E}\right) + j\omega\epsilon^* \tilde{E} - \nabla \left(\frac{1}{j\omega\mu\epsilon^*}\nabla \cdot (\epsilon^* \tilde{E})\right) = \vec{r}_m \tag{8}$$

where $\vec{r}_m$ is the residual due to the error in the FEM solution. In addition to characterizing the error in terms of $\vec{r}_m$, we can also measure the error in terms of the behavior in the magnetic field. It is well known that, in the absence of surface currents, the tangential magnetic field is continuous as any surface. However, the finite element approximation for the magnetic field $\tilde{H}$ is discontinuous at the surfaces which separate the elements in the grid thereby generating fictitious surface currents between the elements. If we define the error in the solution to be $\vec{e}$ where $\vec{e} = \vec{E} - \tilde{E}$, then we can write an equation for the error in terms of the residual $\vec{r}_m$ and the fictitious surface currents. Both of these quantities are calculated directly from the FEM solution for the electric field; therefore, $\vec{e}$ can be computed from a finite element approximation of the expression for the error where the residual and fictitious surface currents act as excitation sources. The details of the derivation is given in a paper which has been submitted from publication [3].

It should be noted that the finite element equations for $\vec{e}$ are formulated in such a way that the error within each element is decoupled from the other elements. Thus, the error is computed very efficiently in an element-by-element manner without the need to evaluate a large matrix equation. The calculated error can now be added to the original electric field solution $\tilde{E}$ to improve the overall accuracy of the numerical solution. It is not necessary to apply this scheme to every element. In many instances, the solution is only important in a small fraction of the elements. For example, in radar cross section (RCS) calculations, we require the field solutions only in the elements which border the outer boundary. Similarly, for scattering matrix calculations in guided wave problems, the only field information required is at the input and output planes of the geometry under consideration. Therefore, for most problems of interest the error calculation occupies only a very small percentage of the memory and computation cost associated with the solution of a problem.

To demonstrate the validity of the method, a three-dimensional finite element program has been written. A frontal scheme [4] is used to solve the sparse matrix equation for the fields. In this report, we present the results of the FEM field calculations and the corresponding error reduction procedures for a propagating TE_{10} mode in an infinite rectangular waveguide. This simple geometry is chosen because the boundary conditions are known. In addition, it is easier to analyze the effectiveness of the method on a simple geometry.

To measure the error reduction, we compare the y components of the original FEM solution ($\tilde{E}_y$) and the improved solution ($\tilde{E}_y + e_y$) to the y component of the exact solution (E_y). The error percentages associated with the original and improved solutions can be found in terms of an energy norm from the equations,

$$ep_1 = \left[\frac{\int\int\int_\Omega |E_y - \tilde{E}_y|^2 \, dv}{\int\int\int_\Omega |E_y|^2 \, dv}\right]^{1/2} \times 100\% \tag{9}$$

$$ep_2 = \left[\frac{\int\int\int_\Omega |E_y - \tilde{E}_y - e_y|^2 \, dv}{\int\int\int_\Omega |E_y|^2 \, dv}\right]^{1/2} \times 100\% \tag{10}$$

where ep_1 and ep_2 are the error percentages for the original FEM solution and the improved solution, respectively.

Let us consider a rectangular waveguide (infinite in z direction) of width 0.6λ (along x direction) and height 0.2667λ (along y direction) where λ is the free space wavelength. The walls of the waveguide are assumed to be perfectly conducting. The problem domain is defined by the walls of the waveguide and two fictitious surfaces located at $z = -1.2\lambda$ and $z = 0$.

Four different mesh densities are chosen to test the effectiveness of the a posteriori error reduction scheme on the above geometry. The four meshes are made up of 72, 144, 240, and 360 elements. The error percentages, ep_1 and ep_2 are listed in the table below for all four meshes.

Waveguide Example	Number of Elements	ep_1 (%)	ep_2 (%)
Case 1	72	41.4	25.7
	144	15.4	9.9
	240	8.3	5.3
	360	3.4	2.9
Case 2	72	34.2	31.3
	144	15.0	14.7
	240	8.5	8.6
	360	5.5	5.6
Case 3	72	47.7	28.8
	144	17.6	10.8
	240	9.5	5.8
	360	6.0	3.7

From the results, it is evident that the scheme produces significant error reduction. Similar results have been obtained for other geometries. We expect that future research in this area will provide even better improvements.

3. A Partitioning Scheme for Electrically Large Geometries

The problem of electromagnetic scattering from complex objects is a major concern in many applications such as radar and communication. In many cases, the scatterer is electrically large as well. Approximate high frequency techniques have been used successfully for many simple geometries, but for more complex structures it is sometimes necessary to use more rigorous numerical techniques such as FEM. Unfortunately, for electrically large scatterers, the number of unknowns may be too large to efficiently use banded matrix solution techniques such as Choleski factorization where the computation time is proportional to NB^2 (N is the number of unknowns, and B is the half bandwidth of the matrix), and the memory storage is proportional to NB. Iterative matrix solution techniques such as the conjugate gradient method can potentially reduce both the computation time and memory storage, and many researchers are currently developing and improving these methods.

In this research, we have chosen to pursue another direction in which we partition the geometry into many small sections. Let us consider the two-dimensional problem of electro-

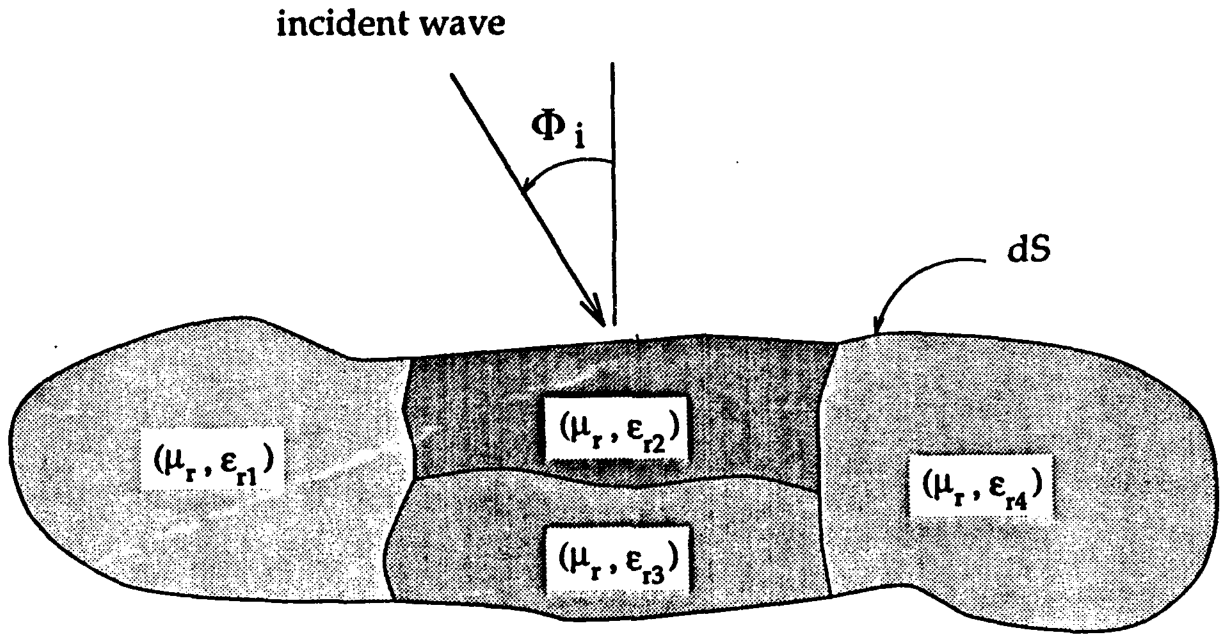

Figure 3: Geometry of an electrically large cylinder with dS representing the boundary of the cylinder.

magnetic scattering from an electrically large cylinder in free space as shown in Figure 3. The surface dS denotes the exterior boundary. In order to separate the formulation of the partitioning scheme from the formulation for the boundary truncation, we consider a boundary value problem in which the Neumann boundary condition is known on dS. The entire cylinder is partitioned into N sections as shown on Figure 4 where $dS_1 \cdots dS_{N-1}$ denotes the interior partition boundaries. dS_0 and dS_N are the left and right boundaries of the cylinder, respectively. On each section, the finite element analysis is applied independently as shown on Figure 5 for the n^{th} section. To find the FEM solution in this section, the boundary condition on dS_{n-1} and dS_n must be known. Unfortunately, they are not known a priori along the interior boundaries. However, the Neumann boundary condition on each interior boundary can be approximated in terms of a sum of known basis functions multiplied by unknown coefficients. We can use the expansions on dS_{n-1} and dS_n to generate a set of finite

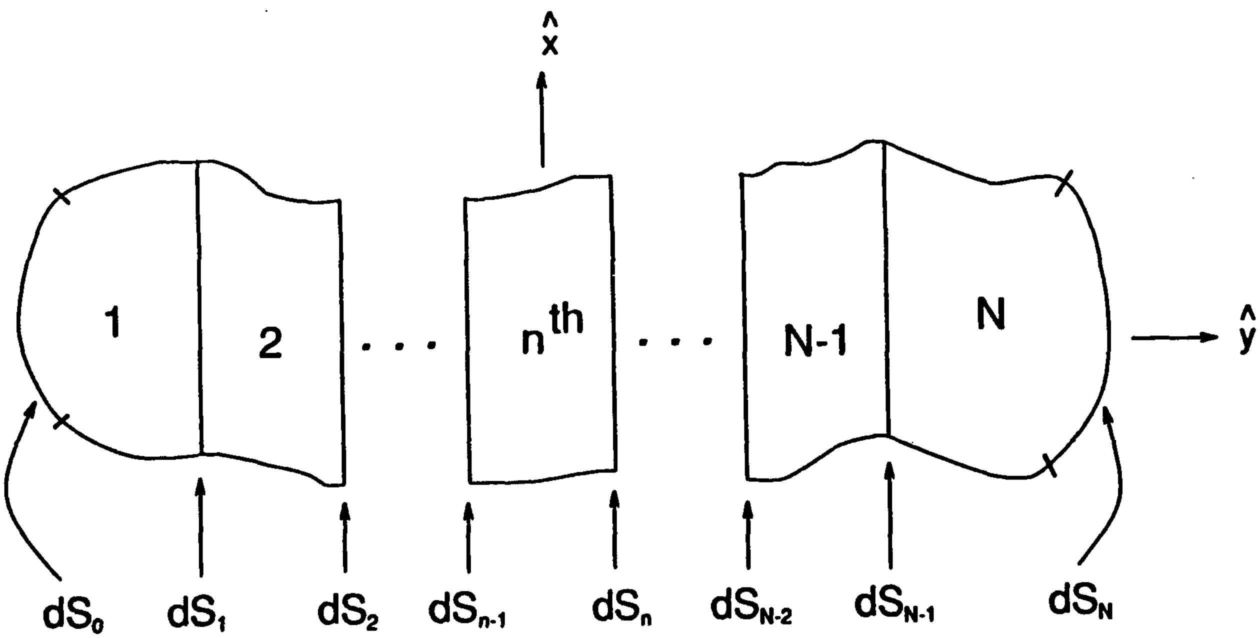

Figure 4: A cylinder partitioned into N sections.

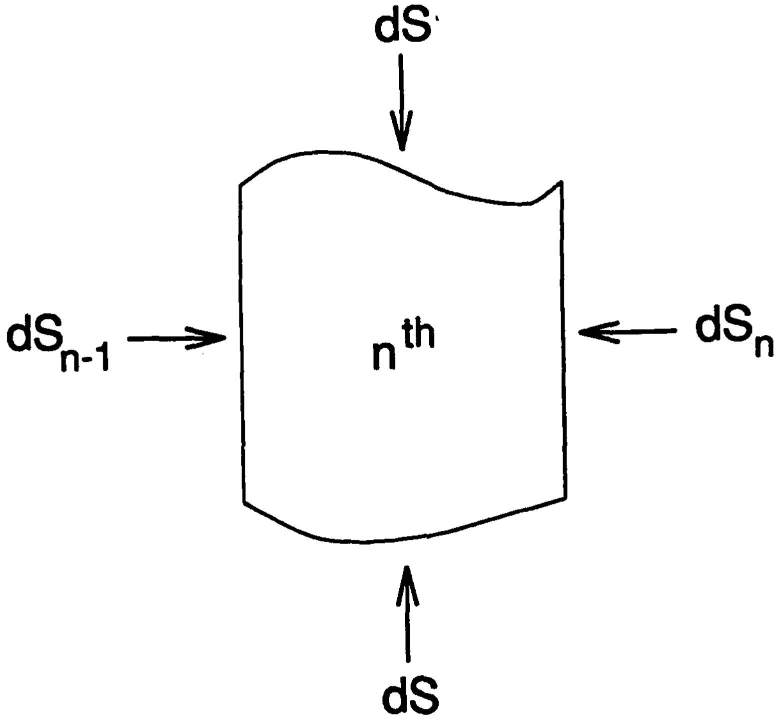

Figure 5: A single section from the cylinder.

element solutions on the n^{th} section in terms of the unknown coefficients. The process can be repeated for each section. Note that although multiple finite element problems must be solved within each section, the matrix equation for each problem only differs in the forcing vector on the right hand side of the matrix equation; therefore if we use Choleski factorization to solve the matrix equation, the factorization only needs to be performed once for each section, and the multiple FEM solutions are generated from performing multiple back and forward solves.

By generating the solutions in each section with the above procedure, we have decoupled the FEM solution in all the sections from one another. Instead, the coupling between the sections is achieved by the proper choice of the unknown coefficients. To evaluate the unknown coefficients on each interior boundary, we enforce the continuity of the tangential electric and magnetic fields at the interior boundaries. After applying these boundary conditions, a method of weighted residual is used to create a matrix to solve for the unknown coefficients. This matrix is block tri-diagonal and can be solved very efficiently.

For example, let us consider the two-dimensional problem of electromagnetic scattering from a $9\lambda \times 9\lambda$ (λ is the wavelength) dielectric cylinder with permittivity $\epsilon = 4\epsilon_0$. The bymoment method is used for the boundary truncation [1]. On the Cray YMP/864, the computation time for the partitioning scheme is only 25% of the computation time needed for the direct solution. In addition, a direct solution requires 40 megawords of memory while the partitioning scheme only requires 3 megawords for this problem. We expect the computational savings to increase as the size of the geometry increases.

4. Boundary Truncation for 3-D Objects

In the previous year's annual summary, a three-dimensional boundary truncation scheme based on the bymoment method was described. Since that time, a three-dimensional finite element program has been written to test the method. Currently, we are considering simple canonical geometries such as a perfectly conducting sphere to validate the method as well as the correctness of the computer code.

There are many difficulties in extending the bymoment method from two to three dimensions. In three dimensions, the boundary truncation must be performed on vector rather than scalar fields. In addition, the bymoment method requires an expansion of the fields on the truncation boundary. For two dimensions, a field expansion on the boundary is easily accomplished because the solution on the boundary can be parametrically mapped to a function of a single variable. In three dimensions, the equivalent problem is to map the tangential fields on the truncation boundary to a function of two variables. Unfortunately, for arbitrarily shaped objects, the mapping is not a straightforward task. Furthermore, the definition of the tangential vectors on an arbitrary surface is not well defined. To overcome the difficulties associated with vectors, we have expanded the field on the boundary in terms of two scalar potentials rather than three vector field components. The use of the potentials not only eliminates vector considerations, but it also reduces the number of unknowns on the boundary by 33%. The problems associated with mapping the fields onto an arbitrary surface is overcome by the use of multipoles as expansion functions on the boundary.

The initial results on some simple geometries show that the method works. It is expected that in the near future the method will be applied to more complex geometries. We can then get a better indication of its robustness and efficiency.

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VI. HYBRID STUDIES

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1. Introduction

When electromagnetic antenna and scattering configurations become electrically large, but also contain substructures which are electrically small, it becomes a rather challenging task to deal with the analysis of such configurations in a tractable fashion, because neither the high nor the low frequency techniques alone can provide a useful solution in such cases. It then becomes necessary to consider a systematic hybrid combination of high and low frequency techniques that are respectively applicable to the electrically large and small portions of the radiating (antenna/scattering) object. The development of such hybrid techniques can be useful, for example, for predicting the radiation and scattering from complex aerospace vehicles and other configurations. The hybrid formulations for the analyses of such complex situations must be done in a self-consistent fashion wherever possible to arrive at a systematic procedure for dealing with a mix of high and low frequency effects that occur on the same radiating object.

In the past, two hybrid combinations of the UTD technique (see the area of Diffraction Studies) and the Moment Method (MM) procedure for solving integral equations for radiation/scattering were developed at the Ohio State University [1, 2]. Those techniques which were illustrated on simple examples were later unified and extended under our JSEP support. For example, the hybrid UTD-MM, or the hybrid MM-UTD methods which then evolved are being employed presently to analyze a variety of stripline antennas. More importantly, the hybrid analysis of printed antennas on planar substrates is being currently extended to deal with the curved (or conformal) substrates. This study, which is based on a hybrid MM-UTD type analysis, is expected to be very useful because it would allow one to very efficiently deal with an antenna or an antenna array on dielectric/magnetic substrate materials which conform, for example, to the metallic skins of aerospace and other types of vehicles. Also, an MM-UTD approach is now almost completed for analyzing electrically large missile shaped objects with fins (vertical and horizontal stabilizers). This work will subsequently be extended to deal with appendages and antenna windows, etc. on such aerospace/missile geometries. It is noted that conventional MM based solutions of such geometries would become intractable at high enough frequencies. Yet another hybrid method which combines an analytical (Wiener-Hopf) method with the generalized scattering matrix technique (GSMT) has been employed to treat a variety of planar guided wave structures (e.g., slot lines, microstrip lines, and different versions of coplanar waveguide geometries). A procedure to minimize the sideways leakage of energy in coplanar waveguides has been found as a result of this study. There has also been good progress made in the hybrid analysis of the radiation from large antennas using some Gaussian Beam (GB) and generalized ray expansion (GRE) techniques, especially when these antennas are to radiate in very complex environments, such as on ships, etc. A hybrid analysis of high frequency ray techniques with the finite difference time domain method (FDTD) is currently under investigation to deal with the efficient analysis of the electromagnetic scattering by inlet/exhaust cavities where the propagation within the cavities is to be treated using ray methods while the complex interior cavity termination is to be treated via FDTD which can accurately model complex terminations/obstacles. Presently, this hybrid ray/FDTD approach has been tested successfully on some simple two-dimensional cavity models and it will be extended in the near future to more realistic three-dimensional situations.

2. Hybrid Analysis of Planar Guided Wave Structures

The effort started last year to study planar transmission lines with a novel scheme which is based on a combination of the Wiener-Hopf and Generalized Scattering Matrix technique (WH/GSMT) has continued this year. The task involves the study of the propagation of electromagnetic fields for a class of microwave planar transmission lines with a top cover and also the study of the mutual coupling between these lines. Examples of these transmission lines are shown in Figure 6. The lateral leakage of higher order modes, the effect of the top cover height and the finite width lateral ground planes for single or coupled microstrip lines, slotlines and coplanar waveguides embedded in multilayer dielectric slabs has been investigated. Although a large number of papers can be found in the literature related to the present study, very few authors have used the present technique. The most commonly used method to handle the present problem is the Spectral Domain approach; however, the GSMT/WH scheme being used here has the advantage of providing much more physical understanding of the behavior of the fields and currents in these transmission line structures. Note that in contrast to the Spectral Domain approach, it is not necessary to assume a basis function for the currents or fields with the WH/GSMT technique because these currents and fields can be obtained from the analysis. Furthermore, the WH/GSMT approach becomes more efficient as the lateral dimensions of the strips, slots, finite ground planes become large. This is in contrast to the Spectral Domain approach where the opposite is true, namely, it becomes more efficient when the lateral dimensions of the transmission lines become small. Thus, the WH/GSMT can complement the more widely used Spectral Domain approach.

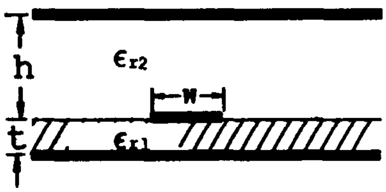
The following tasks have been completed:

(a) The scattering matrix for a PEC half-plane embedded in a multilayer dielectric region with top and bottom PEC ground planes has been developed.

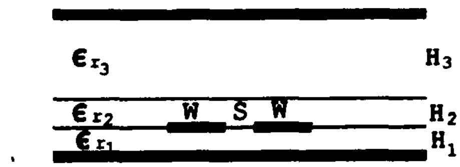
(b) The effect of the finite width of the lateral ground planes for slotlines (SL) and coplanar waveguides (CPW) has been examined to see if some useful design rules for the size of these lateral ground planes can be obtained.

(c) Dispersion curves, lateral leakage of the dominant as well as the higher order modes, characteristic impedance, etc., have been studied for the following planar transmission lines: multilayer microstrip (MS), slot-line (SL), coplanar waveguide (CPW) with infinite and finite side ground planes, and antipodal fin-lines.

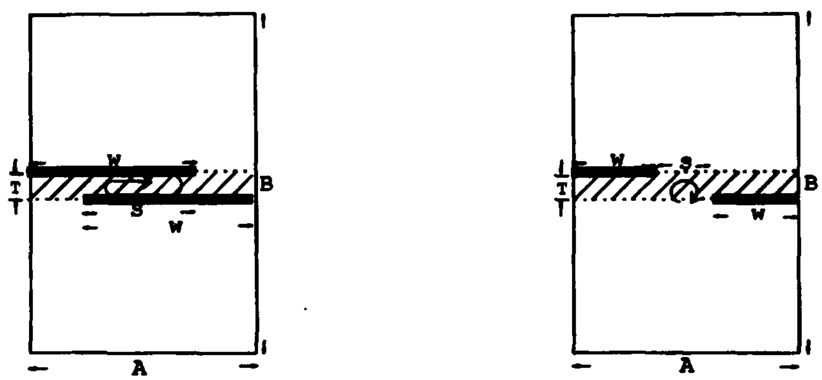
(d) The influence of the height of the top cover on the propagation constants has been investigated.



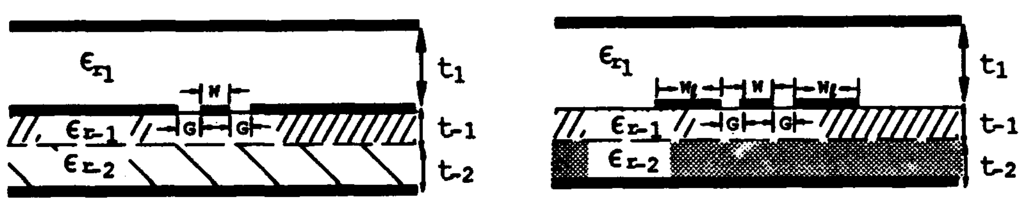
(a) single microstrip line



(b) coupled microstrip lines



(c) overlapped and non-overlapped antipodal finline



(d) conductor backed coplanar waveguide with infinite/finite lateral ground planes

Figure 6:

3. Hybrid Analysis of Conformal Stripline and Antenna Configurations

Work has been completed on developing the solutions to the radiation by arbitrarily oriented elemental antennas on perfectly conducting circular cylinders and spheres which are coated with a dielectric/magnetic material of constant thickness. These solutions have been cast in a form suitable for the asymptotic evaluation of the integrals representing the fields of such elemental antennas in the presence of the coated structures. The next step which has been initiated is the asymptotic evaluation itself which needs to be done carefully to yield the desired UTD solutions which can then be combined with the MM solution for the integral equations governing the currents on striplines, patch antennas or printed circuit antennas on the curved (dielectric/magnetic) material coatings (substrates). Such a hybrid MM-UTD formulation will provide a highly efficient solution for analyzing a large array of printed circuit antennas on a cylindrical or spherical geometry. The efficiency is expected to be almost as good as that which can be obtained for the planar substrate configurations analyzed in the past under JSEP support. Of course, the ability to deal with a large array of conformal printed circuit antenna elements, in the presence of mutual coupling, and on electrically large surfaces with the effects of curvature properly included will be a significant extension over the corresponding hybrid procedure developed previously for the planar case. It is noted that conventional MM based approaches become almost intractable in dealing with large arrays on electrically large surfaces. Eventually, the results will be extended to deal not just with coated circularly cylindrical and spherical surfaces, but also with general convex coated surfaces; the results for the latter case will be developed using the local properties of UTD fields as done previously, under JSEP support, for the non-coated case.

4. Hybrid Analysis of Radiation/Coupling Associated with Large Antennas in a Complex Environment

When electrically large antennas are located over complex platforms it then becomes necessary to discretize the antenna so that ray techniques can be employed to analyze its radiation in the presence of the complex environment. However, conventional discretization schemes require one to shoot a new set of ray tubes into the same complex environment from each of the large number of discretized antenna subdomains whenever the antenna and/or its orientation is changed. In the present study, a novel approach is introduced whereby the fields on the aperture of the large antenna can be expanded efficiently in a set of relatively few Gaussian functions. The coefficients of the Gaussian Expansion can be found in closed form if the antenna aperture distribution is separable; otherwise, it can be found relatively easily via a Galerkin procedure. Furthermore, the near fields of the antenna can be found in closed form from this Gaussian expansion, and these near fields are valid at distances much closer to the antenna than the conventional Fresnel zone distance. In addition, the near field closed form expressions are also automatically valid into the far zone of the antenna (in the absence of the complex environment); thus, a useful by-product of this study is that one obtains a simple closed form representation for the antenna near field to far field transformation. The large antenna is then encapsulated within a mathematical spherical surface (or bubble) whose diameter is not much larger than the antenna. The closed form near field expressions (obtained from the Gaussian expansion of the aperture field) then directly provide the fields of the antenna on the bubble. The equivalent impressed sources on the bubble, which are given by the fields of the antenna on the bubble, then radiate the same fields external to the bubble as does the original antenna which can now be removed from the bubble. Ray tubes are launched radially from an array of pre-selected points on the bubble which now discretizes the bubble into subdomains. The smallest size of the subdomain is dictated by the obstacle nearest to it. Thus, the paths of rays launched from these arrays of points on the bubble do not change even if the antenna or its position is changed within the bubble; only the ray launching coefficients change. Thus, one does not need to shoot new rays into the same complex environment using this generalized ray expansion (GRE) which launches rays from the bubble. This idea has been shown to work well for a large planar phased array with a Taylor distribution that has been selected for the sake of being specific. Other antennas will be treated in a similar fashion. The interaction of the rays with the complex environment, or with another antenna in that environment will be treated in the future. This work is also being supported on a separate grant from the Navy.

5. Hybrid MM-UTD Analysis of Radiation and Scattering

The hybrid MM-UTD scheme has been developed and is almost completed for analyzing the radiation by antennas on or the scattering from a complex object such as a missile or aircraft fuselage with vertical and horizontal control surfaces. The known UTD Green's function for the fuselage is utilized within an integral equation for the unknown currents which are then restricted only to the control surfaces thereby drastically reducing the region over which the unknown currents would reside. In contrast, the conventional integral equation formulations would require the unknown currents to reside over the entire complex structure; such a formulation leads to an almost intractable solution for sufficiently high frequencies. In the process of developing this hybrid technique, an extension of the UTD was required in order to obtain the near field from a source close to but not on the surface of the fuselage. The results were verified by showing that the fields predicted by the new equations blended numerically into those predicted by previous equations valid for sources either directly on or sufficiently far from the surface (fuselage, in this case).

In addition, the use of piecewise sinusoidal basis functions for expanding the unknown currents on the control surfaces were found to be particularly well adapted to this hybrid procedure and therefore also found to be the most accurate. In the very near future, it is proposed to extend this work to include not only the electromagnetic scattering from such an aerospace/missile structure by itself, but to also include the scattering by antennas which might be located on it. It is noted of course that the radiation by the antenna can be calculated in a much simpler fashion (if the antenna currents are known) via the UTD itself as compared to the more complex situation of determining the scattering by an antenna on the complex structure which is illuminated by an external wave. The latter, more complex, situation is of interest here.

6. Hybrid Analysis of the Scattering by a Material Body of Arbitrary Shape in the Presence of an Impedance Wedge

The purpose of this research, which has been recently started, is to study the electromagnetic scattering characteristics of a material body in the presence of a wedge shaped body whose faces satisfy the impedance (Leontovich) boundary conditions. This configuration is depicted

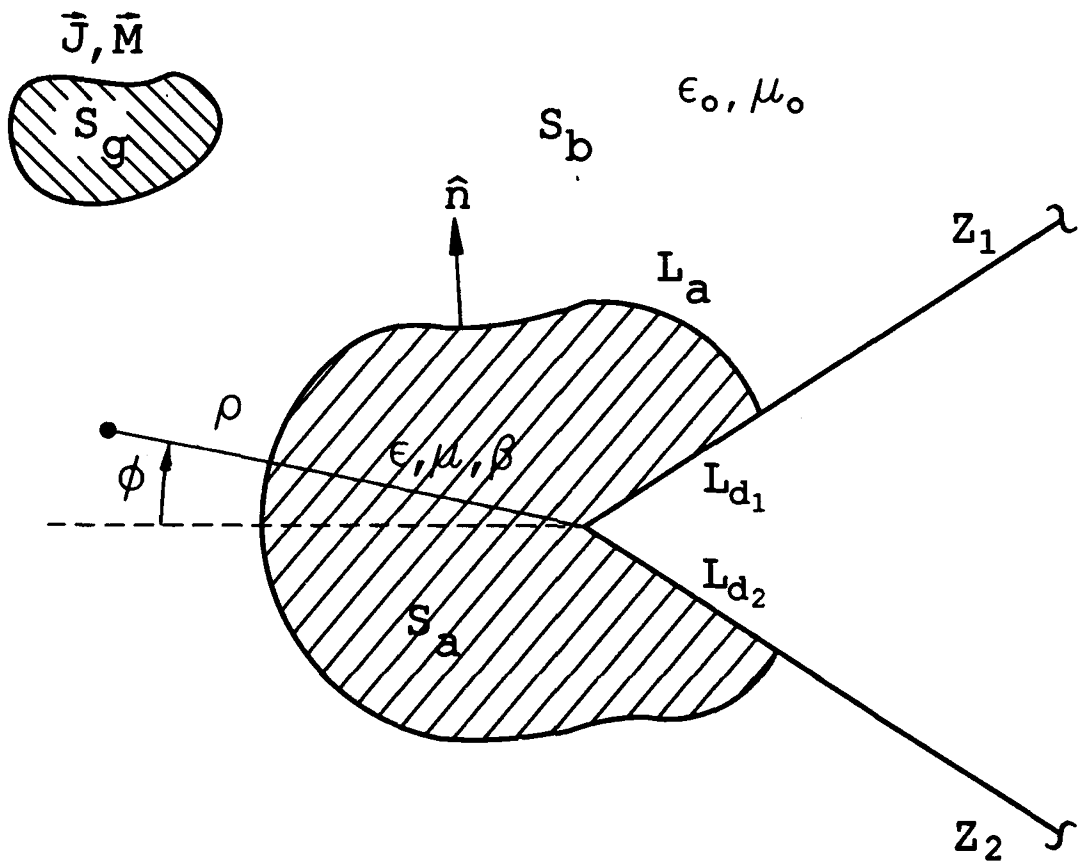


Figure 7: Configuration for a material body in the presence of an impedance wedge where ϵ_1, μ and β are the permittivity, permeability and chiral parameter, respectively.

in Figure 7. The very general configuration of a wedge was chosen for its versatility in representing more specialized geometries. This analysis can have various applications for reducing the electromagnetic scattering from such objects. For example, coating the faces of a conducting wedge with radar absorbing materials can reduce the specular component of the reflected wave. Such thinly coated surfaces can often be approximated analytically by an impedance surface on the faces of the wedge. However, as it will be shown in this research, it is also necessary to treat the tip of the wedge (as shown in Figure 7) to reduce the fields scattered by the tip which can become important and sometimes dominant in some regions.

The analysis to be followed will use the method of moments/Green's function approach where the two dimensional Green's function is that for a wedge with impedance faces. The first part of this research is being devoted to finding a computationally efficient Green's function. There are some papers in the literature where this Green's function is considered; however, none of them give results which would be useful for the present task. The Green's function that will be developed in this study will make use of asymptotic as well as other numerical techniques. The next step in this study will be to obtain a set of integral equations with as few unknowns as possible. There are several types of integral equations that can be used; however, none of the ones found in the literature try to minimize the number of unknowns. The number of unknowns can grow very quickly when material bodies are being considered and thus, it is worthwhile to develop integral equations with the characteristics mentioned above.

7. Hybrid Ray/FDTD Method for Inlet Cavities

Hybrid methods are being widely used by researchers to solve problems which are not easily handled by a single method. One such problem is the electromagnetic scattering from an inlet cavity. The dimensions of the cavity are very large. For example, a typical cavity has a diameter of 40 wavelengths and a length of 100 wavelengths. Low frequency techniques are incapable of modeling structures of this size because of the tremendous computation cost. High frequency techniques can adequately model the cavity, but in most problems the cavity is terminated by a complex structure which cannot be accurately modeled by a high frequency method. Thus, this problem is ideally suited for a hybrid method in which a low frequency method is used to model the termination while a high frequency method accounts for the rest of the cavity.

Currently, most of the hybrid methods employed to solve the cavity problem are done in the frequency domain. In some cases, an integral equation technique such as the method of moments is used to handle the termination in the cavity. Because the termination can have dimensions which are several wavelengths long, the majority of the computation time is spent in the solution of the integral equation. More specifically, the computation time is spent in the solution of a large matrix equation. The number of floating point operations needed to solve a matrix equation is approximately $n^3/6$ where n is the number of unknowns in the matrix equation. In addition, the n^2 elements of the matrix must be stored. For a three-dimensional penetrable termination, the number of unknowns can become so large that the solution of the matrix equation is infeasible in terms of both memory storage and computation time.

Time domain methods such as the finite difference time domain (FDTD) method overcomes many of the difficulties associated with a frequency domain solution. This method evaluates the solution directly in the time domain by stepping the solution in time. Although the solution must be obtained for a multiple number of time steps, it is still very efficient since it does not require the solution of a matrix equation. Instead, the field at a given position in space is computed in terms of the field values in neighboring positions at the previous time step; therefore, the number of floating point operations is proportional to the number of unknowns n. In addition, the memory storage is proportional to n.

FDTD also has another major advantage. In many situations, the time domain response of a pulsed signal is desired. In order to find the solution due to a pulsed signal from frequency domain methods, a numerical solution must be calculated at a multiple number of frequencies (usually on the order of 100~500 frequency points). The time solution is then found from an inverse Fourier transform of the frequency domain solutions. Thus, the amount of computation time needed to find a single time domain solution is further increased by a factor of 100 to 500. FDTD provides the solution directly in the time domain.

In this research, we are developing a hybrid ray/FDTD method for electromagnetic scattering from a cavity. The ray method used is either the generalized ray expansion (GRE) method or the shooting and bouncing ray (SBR) method. The ray methods are frequency domain methods; therefore, in order to couple them to the FDTD, we must either generate a time domain ray solution by employing the inverse Fourier transform or else compute the FDTD solution with a steady state excitation. Work is currently being performed to extend the ray methods to the time domain.

In the hybrid method a ray technique such as SBR or GRE is used to model everything in the cavity except for the termination. SBR and GRE both involve tracing an extremely high number of rays inside the cavity. Rays are "launched" into the cavity and tracked within the cavity as they bounce off the cavity walls until they reach the termination. FDTD then uses the ray solution as the excitation field for the modeling of the complex termination. An absorbing boundary condition is used in the FDTD method at the interface separating the region containing the ray solution from the region containing the FDTD solution. This boundary condition is valid if we assume that the reflections from the complex termination *do not return to the termination.* Because of the shape of the cavity for problems of interest, this assumption is valid.

To test the validity of this method, it has been implemented in two dimensions. In order to obtain an accurate solution, the ray method must produce accurate fields within the cavity. Up to this point, most of the accuracy studies for the ray methods have focused on far-field solutions; therefore, one of the first tasks has been to study the ray solutions within the cavity. We have determined that GRE provides a more accurate interior field solution than SBR.

Although GRE provides a more accurate solution than SBR, it is still an approximate method. We are currently studying how the inaccuracies in the ray solutions may affect the FDTD solution. In the process of performing these studies, numerical results have been generated for several canonical geometries. The initial results indicate that this hybrid method provides accurate far-field solutions.

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